THERMAL BOUNDARY LAYER DYNAMICS AT LARGE RAYLEIGH NUMBER: IMPLICATIONS FOR THE NUMBER OF PLUMES IN PLANETARY MANTLES. E.M. Parmentier, Department of Geological Sciences, Brown University, Providence, RI 02912 (emp@pelee.geo.brown.edu) and C. Sotin, Laboratoire de Geophysique, UFR Sciences, 44072 Nantes Cedex 03, FRANCE.

Mantle plumes, which create topographic swells and volcanism on planetary surfaces, are generated by the instability of a thermal boundary layer at depth [1]. The characteristics of plumes including both their spacing and size have important implications for the characteristics of the thermal boundary layer which creates them. This study examines the dynamics of a thermal boundary layer at high Rayleigh number (Ra) based on 3D numerical experiments in a volumetrically heated fluid cooled from above [2]. Since the bottom boundary of the fluid is insulated, a thermal boundary is present only at the top of the fluid. This allows us to study the behavior of a thermal boundary layer, independent of any effects of interaction with other boundary layers. The unstable thermal boundary layer generates cold plumes that sink through and cool the fluid beneath. For moderately high values of the Rayleigh number, the convective motions are strongly time dependent. New plumes form by boundary layer instability, and plumes disappear by coalescing with other plumes. This behavior has also been observed in 2D numerical experiments and described as a thermal attractor [3].

The average number of plumes present in our 3D experiments, shown in Figure 1, increases approximately as $Ra^{1/4}$. Since the boundary layer thickness δ varies as $Ra^{-1/4}$, the average spacing between plumes varies as $\delta^{1/2}$. This is at first a surprising result since unstable fluid layers are usually thought to generate buoyant upwellings at a spacing proportional to the layer thickness, in this case δ. The dependence of plume spacing on boundary layer thickness can be understood as follows. First, at steady state, plumes must transport the amount of heat internally generated. An estimate of the vertical velocity w in a plume can be derived from a balance of viscous and buoyant stresses $\mu w/d=\Delta\rho g\delta$. The flux of cold fluid in one plume is given by $f = \pi w\delta^2$, and the total heat flux advected by plumes is $Nf\rho c_p\Delta T = Hd$. Here d is the layer thickness, N is the number of plumes per unit area, and H is the rate of volumetric heating. ΔT is the temperature difference across the thermal boundary layer and therefore the temperature increase in a plume. Solving for N and using the estimate for $\Delta T = Hd^2/k\ Ra^{-1/4}$ derived from the numerical experiments gives $N = Ra^{1/4}/\pi d^2$ as observed in our numerical experiments (Figure 1).

The number of plumes present is determined by a balance between the creation rate P of new plumes by boundary layer instability and the rate of disappearance D of plumes by coalescing with other plumes. In general $dN/dt = P - D$ so that $P = D$ at steady state. Estimates for P and D can be derived by simple scaling analysis as above. $P = 1/s^2\tau$ where s is the spacing of plumes and $\tau \approx \delta^2/\kappa$ is the time for the thermal boundary layer to thicken conductively to thickness δ. Note that we assume that plumes are created at the equilibrium spacing s and not at a dominant wavelength proportional to the boundary layer thickness. Plume coalesence is treated as binary fusion with $D = (V/s)N$ where V is the velocity at which two plumes approach. As illustrated schematically in Figure 2, the flow of cold boundary layer feeds each plume. Then the horizontal flow u into a plume can be determined by simple mass balance $\pi s\delta u = f$. Two adjacent plumes which entrain boundary layer at a rate u will approach each other at the velocity $V \approx u$ as shown on the left in Figure 2. Combining these results gives $P = D$ only if at steady state $N \propto Ra^{1/4}$.

The above results for plumes sinking from a cold boundary layer are also applicable to plumes rising from a hot boundary layer. Swells on the surfaces of Earth, Venus and Mars may be generated by plumes rising from a boundary layer at the core-mantle boundary. Based on the results discussed above, the number of active plumes or alternatively the spacing between them is proportional to $(\delta d)^{1/2}$. These planets have 10-40 [4,5], 4-13 [6,7], and 1-2 [8] active plumes respectively. The wide ranges for each planet result from the criteria adopted to define an active plume, for example whether active volcanism is a requirement. The detectability of plumes at the surface may also be strongly affected by factors such as the lithosphere beneath which they rise, for example continents and oceans on the Earth. Nevertheless there appears to be a significant difference in the number of plumes on each planet which, if properly interpreted, must have important implications for the thickness of the boundary layer that creates them. The different number of plumes in Venus and the Earth may further constrain the factors responsible for the significant surface differences observed between these two grossly similar planets.

References: [1] E.M. Parmentier, D.L. Turcotte, and K.E. Torrance, J.G.R. 80, 4417, 1975. [2] E.M. Parmentier, C. Sotin, and B.J. Travis, Geophys. J. Int. 116, 241, 1994. [3] Vincent and Yuen, Phys. Rev. A 38, 328, 1988. [4] J. Phipps Morgan, personal communication, 1996. [5] M.A. Richards, B.H. Hager, and N.H. Sleep, J.G.R. 93, 7690, 1988. [6] S.E. Smrekar, W.S. Kiefer, and E.R Stofan, VENUS II, in press, 1997. [7] F. Nimmo and D. McKenzie, Earth Planet. Sci. Lett., in press, 1997. [8] P.B. Esposito, et al., MARS, eds. Kieffer, et al., U of Az Press, 209, 1992.

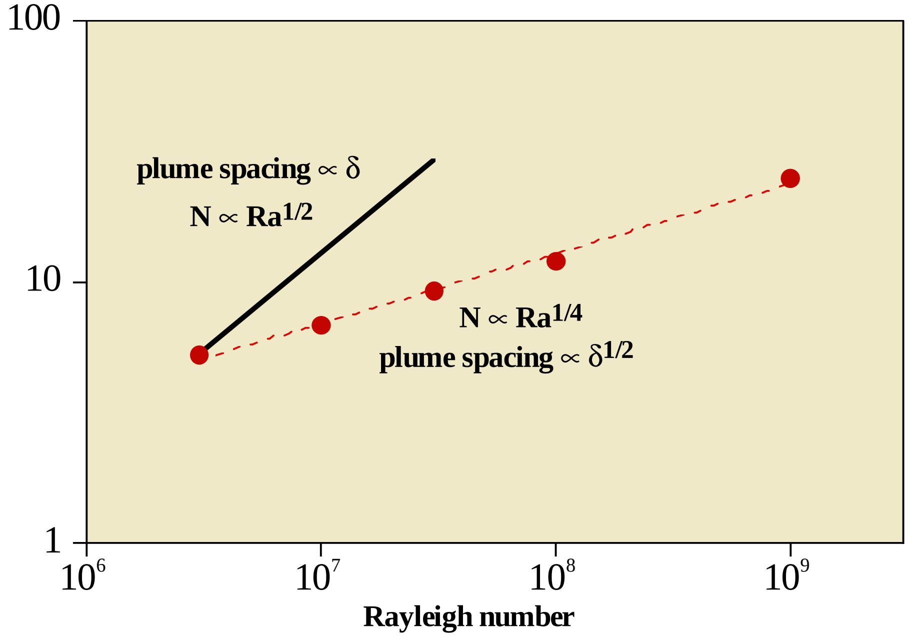

Figure 1. Number of plumes as a function of Rayleigh number for numerical experiments in a volumetrically heated fluid cooled from above. As discussed in the text, the spacing between plumes is not proportional to the thickness of the thermal boundary layer δ which creates. Plume spacing varies as the $\delta^{1/2}$.

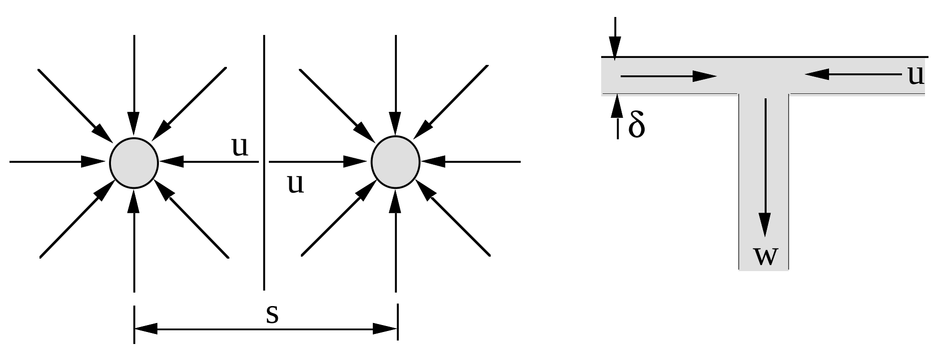

Figure 2. Schematic showing cold boundary layer (shaded) feeding a plume (right) in vertical section and two adjacent plumes in a horizontal plane (left) which entrain boundary layer at a rate u. See text for further discussion.